ANCIENT WATER-PLANES AND CRUSTAL DEFORMATION

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In a recent bulletin of the Wisconsin Geological Survey,[1] Goldthwait has presented the results of an interesting study of the strands of the ancient Great Lakes as they occur in eastern Wisconsin. The field-work is much more detailed and accurate than the average, and the success in reconstructing the complex series of shore-lines of Lake Algonquin, in the region studied, is largely the result of using a wye level, instead of a hand level, or aneroid barometer, in determining the heights of the ancient beaches and terraces above the present lake level as a datum plane.

By far the greater part of the report is devoted to the descriptions of the old shore-lines and a review of previous work. And the conclusions on p. 42 bear only on the history of the ancient Great Lakes. In chap. iv, however, the author takes up the question of the deformation of the Great Lakes region and presents a new hypothesis as to the character of the crustal movements which have deformed the ancient shore-lines.

The hypothesis in brief is: that tilting of the earth's crust took place on the north side of axes which moved northward at intervals, resulting in the originally horizontal Algonquin beach-lines being given a broken profile with progressively steeper slopes northward. The movement was such as to tilt the surface of any block without warping. The idea expressed, it will be seen, is more definite than that of the older hypothesis of "differential warping" and may be spoken of as "differential tilting."

In this article it is desired to analyze the data upon which these hypotheses rest in order to form some idea as to their probable error, and also to compare the two hypotheses in order to see which is the

[1] J. W. Goldthwait, "The Abandoned Shore-Lines of Eastern Wisconsin," *Wisconsin Geological and National History Survey*, Bull. No. XVII, Sci. Ser., No. 5, 1907.

more probable. The result will show that both hypotheses are equally probable, but as that of differential warping involves simpler assumptions, it is considered preferable in our present state of knowledge concerning the subject.

As ideas in regard to the character of crustal movements in the Great Lakes region are based upon the water-planes reconstructed from observations upon the beaches, terraces, and other shore-line features of the ancient Great Lakes, it seems advisable first to consider the several errors that may enter into the determination of the position of such water-planes. These errors have been recognized for many years, and statements respecting most of them may be found in various reports dealing with both the ancient and modern Great Lakes. They have not, however, been collected in any one article, so far as the reviewer knows. It seems appropriate, therefore, to bring them together and point out the limitations they impose upon the correlation of old shore-lines and the deductions that may be drawn from reconstructed water-planes in regard to the character of the deformation of the Great Lakes region, especially as work in this field is now being placed upon a more accurate and refined basis.

The errors that enter into the determination of the height of the ancient beaches, etc., above the present lake levels—the datum planes—need only brief consideration, since with proper care they may be practically eliminated. The principal ones are, perhaps, those connected with the measurements of heights, seasonal fluctuations of the lake level, and changes in level by winds and waves. The first one can only be reduced to a negligible quantity by the use of a wye level, the instrument adopted by Spencer, Lawson, Upham, and Goldthwait in their work. The second may be eliminated by applying to the altitude determinations a correction obtained from a continuous record of the fluctuation of the lake level, a correction that was applied by Goldthwait. The last two errors appear rather troublesome, though they may be largely eliminated by restricting work to calm days. To do this, however, might often prove inconvenient, and it may be assumed that an error of from 1 to 2 feet[1] may arise from these causes.

The more important errors are connected with the location of water-planes with respect to ancient beaches and terraces, with the

[1] Goldthwait, *op. cit.*, p. 100.

former larger fluctuations in water-levels, and with other points that will be taken up in categorical order.

1. The exact position of an old water-plane is very difficult to determine because of its variable relation to different beaches, terraces, and other shore forms. The common practice has been to take the top of a beach ridge as fixing the position of the old water-plane, "although it is of course recognized that the beach ridge probably stood anywhere from 3 to 6 feet above the actual water-plane."[1] If in the case of a true beach ridge the actual water-plane will average 3 feet below the top of the ridge, elevations should be corrected by this amount in order to bring them as near the true water-plane as possible. If observations were entirely upon beaches this correction would be a constant and might be omitted in considering the relative displacements suffered by the shore-lines. But as they are also made upon terraces, spits, and bars, which require different assumptions in regard to the height of the water-plane, the above correction should be applied, otherwise the observations are not comparable within the assumed limit of 3 feet. In the case of a cut terrace the foot of the bluff is taken as fixing the position of the water-plane, although the true water-plane may have been as much as 2 feet either above or below that point. Where a terrace is cut in unconsolidated material the actual water-plane would in most instances be above the foot of the bluff and a correction might be applied to allow for this. Where terraces are cut in rock its location would depend upon the character and dip of the strata. In this instance a close study of present conditions might furnish a correction that could be applied in certain cases at least.

2. The variability in the position of a beach ridge with respect to the water-plane may particularly be noted. While a "normal" beach may be 3 feet above the surface of the water, storm beaches as much as 6 feet above the lake level may be considered as common, and a few have been reported at still higher elevations. Unless such beaches are situated so that their true nature can be recognized by comparison with neighboring shore-line features, they may introduce serious errors. One will be noted in the next paragraph. Storm beaches are formed, of course, only on the exposed parts of the shore-

[1] Goldthwait, *op. cit.*, p. 100.

line and evidently vary in height on the shores of different lakes. The configuration of the shore and its relation to the direction of storms exercise a great influence on the height of such beaches, and many interesting observations have been made on this point.[1] Lawson states[2] that on the north shore of Lake Superior he measured crests of living beaches facing the open lake at all elevations between 9 and 14 feet above calm water, while in less exposed parts of the shore they did not usually exceed 6 feet in height. Goldthwait,[3] for the western shore of Lake Michigan, sets the upper limit at 6 feet, and in one instance possibly at 8 or 9 feet. A correction should be applied to Lawson's figures, at least, to allow for the drop in the lake level from the high-water stage of 1886 to the 1891 stage on which his observations were based. This correction may be taken at 2 feet, so that the figures read 7, 12, and 4 feet, respectively. The error introduced by the variable position of a beach may be placed at 4 feet, allowance being made for the 3-foot correction above noted.

3. Cyclic fluctuations in water-level of the ancient lakes, due to short climatic variations, no doubt occurred as they do in the present lakes. The Milwaukee (Wis.) record shows an average change of 1.5 feet in the level of Lake Michigan from summer to winter. Lane says: "The water-level of the lakes at those (former) times undoubtedly varied from year to year and from month to month as it does now, probably in even more marked degree, as the cold of winter would have even more effect in checking the flow of water from the ice sheet;"[4] while Upham states: "Fluctuations of the lake level (in Lake Agassiz), which doubtless rose in summer a few feet higher than in winter because of variations in the volume of water supplied, have given a variability within the limits generally 5 feet and perhaps sometimes 8 or 10 feet apart to the heights of the lake and of its shore deposits

1 Chas. Whittlesey, "Fluctuations in the Level of the North American Lakes." *Smithsonian Contributions to Knowledge.* Vol. XII; A. J. Henry, "Wind Velocity and Fluctuations of Water Level on Lake Erie," *U. S. Weather Bureau*, Bull. J., 1902.

2 A. C. Lawson, "Coastal Topography of the North Side of Lake Superior," *Geological and National History Survey of Minnesota*, Twentieth Annual Report, p. 231.

3 Personal communication.

4 A. C. Lane, "Geological Report on Huron County, Michigan," *Geological Survey of Michigan*, Vol. VII, Pt. II, p. 65.

in different stages."[1] Much more important, however, are the changes in level that occur over a period of years rather than months. The record of the fluctuations of lakes Michigan and Huron from the year 1800 to 1899[2] is most instructive upon this point. The maximum change of level shown is 6 feet, while the average fluctuation between successive high and low stages, for all changes over 1 foot, is about 2.5 feet. What then is the true water-level? The question has a very direct bearing on the problem of fixing the position of the water-planes of the glacial Great Lakes from observations upon their shore-lines, since one beach formed in one decade might well be several feet higher or lower than a second constructed at another point in a following decade. Lane has noted the effect of such fluctuations in speaking of a 14-foot beach ridge in Huron County, Michigan. He says: "The water-line probably lay a little lower, at 10 or 11 feet above the 582-foot datum (the present lake level), at a time perhaps within range of tradition. . . . . The high water-line of 1886 is well marked in a crest from 4 to 7 feet above the present lake level."[3] The idea naturally suggests itself that a reconstructed water-plane, when drawn on a large enough scale, instead of being represented as a single line, should be shown as a zone of such a width as would take account of these changes of level.

As an extreme case, it may be supposed that at a time of maximum high water a storm beach was built up 6 feet above the water-level, while at a time of low water a terrace was cut 2 feet below the lake level. There would be a difference of 14 feet (8 in beach and terrace +6 in water-level) between the two, yet they would belong to the same period and might have been formed within 25 years of each other. Such an explanation may account for the discrepancy (of 10 or 12 feet) between a cut terrace and bowlder beach on the north shore of Lake Superior which Taylor believed belonged to the same shore-line. He says: "Measurements of the same shore-line often vary 7 or 8 feet, sometimes more, from this cause"[4] (one measure-

[1] W. Upham, "The Glacial Lake Agassiz," *U. S. Geological Survey, Monograph 25*, p. 277, 1896.

[2] Lane, *op. cit.*, Plate V.

[3] *Op. cit.*, p. 76.

[4] F. B. Taylor, "The Nipissing Beach on the North Superior Shore," *American Geologist*, Vol. XV (1895), p. 307.

ment on a beach, the other on a terrace). Such discrepancies as just noted may give rise to large errors (50 per cent. or more) in the calculated gradient of a shore-line when the distance between the two points of observation is short. These larger fluctuations in water-level would prove especially troublesome where strong cutting or filling was occurring. When the water-plane is gradually dropping a blurring of shore forms frequently results, although this is not always the case as Goldthwait's profile at Jacksonport shows.[1] On the other hand, if the water-level remained constant for several years a well-marked terrace might easily be cut or a strong beach built, while with a drop to a new level, at which the water might again stand for some time, a second terrace or beach might be formed. As the record shows, differences of 2 or 3 feet would be common between such terraces and beaches. It seems difficult to escape the conclusion that a source of error in the reconstruction of water-planes exists here that cannot be eliminated. It may range from 0 to 6 and possibly a larger number of feet.

4. The quotation from Taylor, above given, raises the question whether the level of a water-plane can be judged more closely from cut terraces or beaches. From the fact that beaches show such wide variations in position with respect to the water-plane, it would seem probable that terraces furnished the best guide. Upham has stated: "Cliffs eroded by the lake waves give more definitely the plane of the water surface"[2] than beaches. This applies, however, only where the forms are well preserved. When they are not well preserved, it seems likely that a beach would be a better guide than a terrace, since the original surface of a terrace is more liable to become obscured than that of a beach. This brings up the point that both beaches and terraces in time become more or less eroded and covered with vegetation, thus making it difficult to tell just what point should be chosen in measuring their elevations, and leading to uncertainty in correlation. Lawson has said, in speaking of a certain locality on the north shore of Lake Superior, that "a series of terraces can be seen scoring the hills to the north at a distance of probably a little more than a mile and a half at the farthest. An effort was made to locate these terraces by running a line of levels from the railway, but this

[1] *Op. cit.*, p. 76. [2] *Op. cit.*, p. 277.

met only with partial success. The terraces which appeared so sharp and unequivocal from the railway station lost their character when approached closely, and could be recognized as terraces only with considerable doubt."[1] What error may be introduced through the alteration of original forms is difficult, perhaps, to say. In the case of beaches it would be small as compared with that resulting from the variable height of a beach above the water-level. For terraces the error would generally be somewhat greater, since the base of a bluff is frequently obscured by talus, wash, etc. An error of 1 foot may be assumed as due to this cause.

It will be recognized, of course, that observations in the field, that is, our so-called geologic facts, vary greatly in value, and in any refined work should be weighted accordingly. Observations on the ancient shore-lines, however, serve two purposes. The first is to unravel the history of the glacial Great Lakes and as continuous tracing of shore-lines is a very important part of this work, observations should be as numerous as possible. The second is to determine the character of crustal movements in the Great Lakes region. This is a different problem and the value of results depends upon the probable error of observation. In refined work this error should be reduced to a minimum, for which reason it would seem advisable to use, if possible, only those observations that have small errors.

5. Progressive climatic changes over long periods of time may also have produced important variations in the water-levels of the lakes. That such climatic changes occurred may reasonably be inferred from the pronounced movements of the continental ice sheet during that period. This factor may well have been of considerable importance, but is at present undeterminable. It is simply presented as one of the unknown factors in the problem of the history of the ancient Great Lakes which might alter conclusions were its value known.

6. Secular changes in the water-level due to (1) show crustal movements, and (2) changes produced by erosion in the elevation of outlets are to be noted. Errors arising from these sources may eventually be eliminated—when the history of the ancient lakes has been worked out in fuller detail. Attention, however, may be called to one condi-

[1] *Op. cit.*, p. 263.

tion which must be taken into account, namely, the gradual lowering of the water-level from one stage to another. The condition is similar to that described under (3), but is of greater magnitude. It necessitates representing the water-planes as zones of such a width as will include these variations in water-level.

7. Variations in the elevations of the old shore-lines would result from deformation of the water-level induced by local attraction of the ice sheet. The error introduced is small, though it would have to be taken into account in any consideration of the old shore-lines as a whole. For small areas, presumably remote from the ice sheet, it may be neglected.

It will be seen from the foregoing that there are several noticeable errors connected with the location of a water-plane with respect to ancient shore-lines. A calculation, which takes account of only the more important errors, gives the probable error of observation as ± 1.5 feet, the limit of error 10 feet.

While these errors affect to some extent the correlation of a series of ancient beaches, terraces, and related shore forms, it is desired to point out here the influence they have upon conclusions, based on the present attitude of the reconstructed water-planes, as to the character of the crustal movements in the Great Lakes region. This may be illustrated by fitting curves of different kinds to Goldthwait's very complete set of observations as they are plotted on Plate XXXVII of his report.

We may consider first that portion of the profile extending from Rock Island to Jacksonport, a distance of 35 miles, since this is the stretch in which the several ancient water-planes have been individually distinguished. For the sake of simplicity a straight line may be drawn through each of the series of observations representing the four water-planes *A*, *A′*, *B*, and *C*. The deviations of all points of observation in each series from its respective straight line may then be measured, and likewise from the broken lines as drawn by Goldthwait. The results are as follows:

Average deviation of all sure points from straight	lines	= 1.4	feet.
" " " " " " " broken	"	= 1.1	"
Maximum deviation of any sure point from straight	"	= 4.0	"
" " " " " " " broken	"	= 4.0	"

Both the average and the maximum deviation in each case are within the probable error of observation and the limit of error respectively, so that the difference of 0.30 foot in favor of the broken lines possesses no significance. It may be shown likewise that a curved line would fit the observed points with no greater error than noted above.

The certain conclusion is reached, then, that either a straight, a curved, or a broken line may be drawn through the points of observation with equal accuracy, and that, consequently, in this distance of 35 miles the present attitude of the old shore-lines may be the result either of a uniform tilting, a differential warping, or a differential tilting of the earth's crust.

It may be said, however, that a distance of 35 miles is too short for a test of this character. We may consider, then, the entire length of the profile from Rock Island to Two Rivers, a distance of about 100 miles. In so doing the conclusion that the Algonquin beaches encircle the southern half of Lake Michigan as the "Toleston" beach, instead of descending beneath the level of the lake somewhere north of Two Rivers, will be assumed as correct.

The first thing to be noted is that a straight line cannot be drawn through the points of observation without far exceeding the probable error of observation. The hypothesis of uniform tilting, therefore, drops out. It appears possible, however, to fit a curve. For the sake of simplicity a circular curve, with a radius of approximately 11.75 feet, may be drawn through the points of observation as plotted on Goldthwait's profile, and the deviations of the points measured. The results are as follows: Average deviation of all sure points = 1.2 feet; maximum deviation of any sure point = 3 feet. The deviations of all the observed points from the broken profile of Goldthwait were not measured for the entire length of the profile, since it was evident that they would be essentially the same as measured for the profile from Rock Island to Jacksonport, namely, 1.1 and 4.0 feet respectively.

The conclusion may be stated, then, that the Algonquin shoreline for the whole length of the profile, about 100 miles, furnishes no evidence in favor of the hypothesis of differential tilting over the older one of differential warping; both are equally probable so far as the observations go. The hypothesis of differential warping, however,

involves a simpler assumption respecting the distribution of stresses within the earth's crust, and for this reason should be considered preferable to the hypothesis of differential tilting.

If earth movements in the Great Lakes region had been great instead of small, and the errors in the water-plane determinations small instead of great, the character of the crustal deformations might well be ascertained; but on the contrary we find the probable error of observation so large—it is expressed in feet, rather than tens of feet or in inches—that it leads to the impression that but little refinement of the old idea of differential warping is possible on the basis of the ancient shore-lines alone.